I – Problem Statement Title (EQ 066)

Development and Validation of Design Guidelines for Bridge Systems supported on Spread Footings Allowed to Uplift During Earthquakes

II – Research Problem Description

Question: What confidence can be placed in guidelines developed for the design of bridge columns supported on spread footings permitted to uplift during earthquakes?

Research has indicated that permitting spread footings supporting bridge piers to uplift during earthquakes can not only reduce construction costs associated with using larger spread footings or pile foundations in order to restrain up lift, but that the post earthquake damage to the column can be substantially less, and the column may have very little residual lateral displacement in comparison to traditional fixed base designs. The nonlinearity introduced by the rocking mechanism in combination with energy dissipation associated with localized soil inelasticity appear to be sufficient to limit the overall lateral displacements of a simple bridge structure to values comparable to traditional designs undertaken by Caltrans and other bridge engineers. Recent earthquakes, like the 1979 Imperial Valley, 1995 Kobe and 2004 Niigata earthquakes, appear to confirm the effectiveness of this mechanism in principle. AASHTO and other provisions include provisions for uplift in the design of spread footings. Preliminary seismic design guidelines are currently being developed for rocking spread footings as part of an integrated structural and geotechnical engineering research programs sponsored by Caltrans at the UC Berkeley and UC Davis. While these investigations have examined a wide range of parameters, and carried out 3D shaking table tests of single columns, a number of questions remain before designers have full confidence in this approach.

III – Objective

Roadmap Outcome: 5 - Improved Soil-Foundation-Structure-Interaction Analysis Tools, Techniques, and Methods (Problem 8: High Foundation Cost)

Verify the concept of foundation rocking in order to reduce seismic demand, and carry out tests necessary to establish confidence in design procedures applicable to realistic bridge systems.

IV – Background

Rocking mechanisms have been observed to be key factors in preserving many ancient structures around the world, as well as many modern ones. While simplified design guidelines are being developed specifically for the design and analysis of bridge piers supported on spread footings allowed to rock during severe earthquakes, these guidelines have not been fully assessed in terms of many real world situations encountered in bridge design. Thus, research and verification testing is needed to deploy this promising approach with confidence. Issues requiring additional effort include nonlinear dynamic analyses and geotechnical centrifuge/shaking table tests of simple bridge columns, and especially bridge systems, under earthquake excitations. Shaking table tests of reasonably scaled complete systems, and geotechnical centrifuge tests of complete systems (for example, curved bridges) are of particular priority. Overall, numerous factors should be considered, including some from the following list:

- A more extensive array of soil conditions;
- Restraint at the top of columns provided by the superstructure. The bridge deck may restrict vertical movement of the columns, preventing the uplifting mechanism from occurring and transfer significant axial load, or induce unexpected plastic hinging in columns (Typically, it is expected that the columns need to be ductilely detailed according to current Caltrans practice).
- The restraint provided to differential vertical movement of top of the columns superstructure when columns with different lengths or foundation sizes are used in the same bridge having a monolithically constructed superstructure. These columns will rock by differing amounts and this may significantly affect the overall rocking response of the system.
- Column height and flexibility (including higher mode effects in the columns);
- Simultaneous yielding of the column and rocking of foundation;
- Presence of water at the elevation of the base of the spread footing. Concern has been raised regarding suction that may increase the uplift capacity of the foundation, and the tendency of the footing to float when the gap at the base of a footing closes;
- Effect of potential soil inelasticity or settlement on response during subsequent earthquakes.
- Axial load amplitudes beyond 10%$A_g f'_c$;
- The adequacy of various design oriented analysis and evaluation criteria;
- In the case of older bridges with insufficient tension anchorage of the piles to the pile cap. Pile tensile fracture may affect overall dynamic response, and local damage in the pile cap, column to cap connection, and pile.
- Comparison with AASHTO and other guidelines related to uplift of foundations.
- Case study designs and analyses based on preliminary guidelines and conventional and refined numerical analyses.

V -Statement of Urgency, Benefits, and Expected Return on Investment

This research builds upon current on-going research funded by Caltrans, and other efforts being under taken worldwide. Thus, it will take advantage of the momentum and synergy of efforts being taken by various groups. The concept of rocking spread footings will eliminate the need to use larger footings or install piles where rocking on competent soil can be relied upon. It will reduce damage to columns and the superstructure, as many of the deformations that are developed in these elements in a conventional fixed base design will be absorbed by the rocking response. Moreover, a properly designed bridge having spread footings allowed to uplift will have little or no residual displacement following a major earthquake. Thus, research to speed implementation of a lower cost solution that has improved post-earthquake functionality has high priority and high potential payoff.

VI – Related Research

Considerable research has been carried out related to the uplifting of simple bridge like structures supported on spread footings, which suggests that this mechanism is effective in reducing cost, shortening construction schedules, and minimizing post earthquake damage, including residual displacements. For example:

- Housner, G.W. (1963). "The Behavior of Inverted Pendulum Structures During Earthquakes." *Bulletin of the Seismological Society of America,* SSA 52(2).
- Chopra, A. K. and Yim, C., (1983). "Simplified Earthquake Analysis of Structures with Foundation Uplift." *Structural Engr.,* ASCE, Vol. 111, No. 4, April 1985.

Recent bridge specific research is being supported by Caltrans:

- Alameddine, F., and Imbsen, R.A., (2002). "Rocking of Bridge Piers Under Earthquake Loading." Proceedings of the Third National Seismic Conference & Workshop on Bridges and Highways.
- Espinoza, A., Mahin, S., Jeremic, B., Kutter, B. and Ugalde, J., [1] ROCKING OF BRIDGE PIERS SUBJECTED TO MULTI-DIRECTIONAL EARTHQUAKE LOADING, Proceedings, Caltrans Seismic Bridge Research Workshop, Sacramento, CA Oct. –Nov. 2005

In addition, relevant research is underway in Japan:

- Kawashima, K. and Hosoiri, K. (2003). "Rocking Response of Bridge Columns on Direct Foundations," *Proceedings,* Symposium on Concrete Structures in Seismic Regions, Paper No. 118, FIB, Athens.
- Sakellaraki, D., Watanabe, G. and Kawashima, K. (2005). "Experimental Rocking Response of Direct Foundations of Bridges, *Proceedings,* "2nd Int. Conf. on Urban Earthquake Engineering, March 7-8, 2005, Tokyo Inst. of Technology, Tokyo, Japan.

VII - Deployment Potential

This work is an extension of on-going work in the US and Japan, which directly addresses some remaining impediments to the application of the uplift and rocking response of shallow spread footings for bridge columns. To date, results are promising, and general design guidelines are being developed at UC Berkeley and UC Davis based on the results of the first phase investigations. However, it appears that full acceptance and deployment of this concept requires specific additional tests and analyses, focusing on several unresolved issues and validation of design guidelines. Rapid deployment would be expected following completion of these validation studies